



(12)

EUROPEAN PATENT APPLICATION

(43) Date of publication:  
31.07.1996 Bulletin 1996/31

(51) Int. Cl. 6: G01R 33/422

(21) Application number: 95309282.2

(22) Date of filing: 20.12.1995

(84) Designated Contracting States:  
DE FR GB NL

• Zou, Xueming  
Chesterland, Ohio 44026 (US)  
• Morich, Michael A.  
Mentor, Ohio 44060 (US)

(30) Priority: 27.01.1995 US 379979

(74) Representative: McGowan, Nigel George et al  
The General Electric Company plc  
GEC Patent Department  
Waterhouse Lane  
Chelmsford, Essex CM1 2QX (GB)

(71) Applicant: PICKER INTERNATIONAL, INC.  
Cleveland, Ohio 44143 (US)

(72) Inventors:  
• Richard, Mark A.  
Cleveland Heights, Ohio 44121 (US)

(54) Magnetic resonance apparatus and methods

(57) A magnetic resonance apparatus includes a magnet assembly (10) for generating a temporally constant primary magnetic field through an examination region disposed in a central bore (14). The central bore is surrounded by a gradient coil assembly (30) including a dielectric former (32) and gradient coils (34, 36, 38) for generating magnetic field gradient pulses across the examination region. A radio frequency coil assembly (50) including a birdcage coil (54) is mounted inside of the gradient coil assembly and surrounding the examination region. The apparatus further includes a radio frequency shield (60) including a dielectric sheet (62) having a plurality of first metal foil strips (72) defined on each surface. The metal strips are suitably defined by etching or cutting gaps (70) in a continuous sheet of copper foil, leaving bridges (74) across the gaps adjacent opposite ends of the foil strips. The foil strips on opposite faces of the dielectric sheet are offset by half the width of one strip such that each strip is capacitively coupled to two strips on the opposite surface. The radio frequency coil induces radio or megahertz frequency eddy currents to which the capacitive coupling appears as a short-circuit, allowing the induced radio frequency currents to pass circumferentially around the shield. The gradient coil assembly induces kilohertz frequency eddy currents to which the capacitive couplings appear as open circuits. The kilohertz eddy currents flow longitudinally along a strip, cross a bridge adjacent one end of the strip, and flow back longitudinally along an adjacent strip, and so forth.

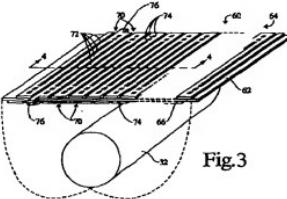


Fig. 3

## Description

This invention relates to magnetic resonance apparatus and methods. It finds particular application in conjunction with cylindrical bore magnetic resonance imaging apparatus with annular magnets and will be described with particular reference thereto. However, it is to be appreciated that the invention also finds application in conjunction with magnetic resonance spectroscopy apparatus and other types of magnetic resonance imaging apparatus.

Heretofore, magnetic resonance imaging apparatuses have commonly included a series of annular superconducting magnets surrounded by a toroidal vacuum dewar. Gradient magnetic field coils were disposed circumferentially around a central bore of the vacuum dewar, often supported on a dielectric cylindrical former. A radio frequency coil was commonly disposed inside of the gradient coils, often on another cylindrical former.

In order to maximize the size of the central patient receiving bore, hence the size of the patient which could be received, it was desirable to mount the radio frequency coil on as large a diameter cylinder as possible. On the other hand, the cost of the superconducting main field magnets increased with size and diameter. Hence, it was desirable to make the main field magnets as small a diameter as possible. In magnetic resonance imaging, the gradient field coils were called upon to create magnetic field gradient pulses. The sharpness or crispness of the magnetic field gradient pulses was a limiting factor on the resolution and sharpness of the resultant image. The smaller the size, i.e., the smaller the diameter, of the gradient field coils, the sharper and more crisp the gradient field pulses tended to be due to increased efficiency and slew rate and reduced eddy current effects from interaction with cold shields. In order to accommodate these competing interests, the radio frequency and gradient magnetic field coils were typically mounted close together such that both had nearly the same diameter.

The gradient coils are pulsed by applying pulses of high amperage kilohertz frequency current. The high power pulses applied to the gradient coils created electrical noise which corrupted the signal received by the radio frequency coil. To protect the radio frequency coil from this noise, a metallic shield was typically located between the gradient coil and the radio frequency coil. In general, the thicker the layer of metal, the more effective the shielding. Often, the metallic shield was positioned either on an inside diameter of the dielectric former which carried the gradient field coils or was laminated to the exterior diameter of the dielectric former before the gradient coils were applied; see, for example, European Patent Specification No. 0629875A of Morich, DeMeester, Patrick, and Zou.

In order to meet clinically driven demands for faster higher resolution imaging, the gradient strength and slew rate have been increasing, i.e., the gradients are becoming larger and crisper. One difficulty encountered

was that the large gradient pulses induced corresponding eddy currents in surrounding metal structures, such as the metallic shield. The eddy currents limited the slew rates.

- 5 One approach for limiting eddy currents was to cut the solid copper sheet into smaller elements to reduce the size of the material available to conduct eddy currents, hence reduce eddy currents. See, for example, U.S. Patent No. 4,642,569 of Hayes and US Patent No. 10 5,243,286 of Rezedian.

One approach for limiting eddy currents was to replace the solid copper sheets with a copper mesh. Because the mesh typically had less metal than the metal sheets, shielding was compromised. Another approach was to replace the solid copper sheets with strips of copper tape coated with an insulator. The tape extended longitudinally along the cylinder and adjacent tape strips were lapped to create a capacitive coupling. The effective capacitive coupling between the lapped copper tape strips provided an effective short circuit for radio frequency currents, e.g., in the megahertz range. However, the capacitive coupling appeared as an open circuit to low frequency components. One of the disadvantages of the lapped copper tape was that the low impedance path for RF currents was enhanced by very thin dielectric coatings on the strips. First, it was relatively difficult to obtain sufficiently thin dielectric coatings on the tape or strips. Second, thinning of the dielectric coating promoted arcing.

- 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110 115 120 125 130 135 140 145 150 155 160 165 170 175 180 185 190 195 200 205 210 215 220 225 230 235 240 245 250 255 260 265 270 275 280 285 290 295 300 305 310 315 320 325 330 335 340 345 350 355 360 365 370 375 380 385 390 395 400 405 410 415 420 425 430 435 440 445 450 455 460 465 470 475 480 485 490 495 500 505 510 515 520 525 530 535 540 545 550 555 560 565 570 575 580 585 590 595 600 605 610 615 620 625 630 635 640 645 650 655 660 665 670 675 680 685 690 695 700 705 710 715 720 725 730 735 740 745 750 755 760 765 770 775 780 785 790 795 800 805 810 815 820 825 830 835 840 845 850 855 860 865 870 875 880 885 890 895 900 905 910 915 920 925 930 935 940 945 950 955 960 965 970 975 980 985 990 995 1000 1005 1010 1015 1020 1025 1030 1035 1040 1045 1050 1055 1060 1065 1070 1075 1080 1085 1090 1095 1100 1105 1110 1115 1120 1125 1130 1135 1140 1145 1150 1155 1160 1165 1170 1175 1180 1185 1190 1195 1200 1205 1210 1215 1220 1225 1230 1235 1240 1245 1250 1255 1260 1265 1270 1275 1280 1285 1290 1295 1300 1305 1310 1315 1320 1325 1330 1335 1340 1345 1350 1355 1360 1365 1370 1375 1380 1385 1390 1395 1400 1405 1410 1415 1420 1425 1430 1435 1440 1445 1450 1455 1460 1465 1470 1475 1480 1485 1490 1495 1500 1505 1510 1515 1520 1525 1530 1535 1540 1545 1550 1555 1560 1565 1570 1575 1580 1585 1590 1595 1600 1605 1610 1615 1620 1625 1630 1635 1640 1645 1650 1655 1660 1665 1670 1675 1680 1685 1690 1695 1700 1705 1710 1715 1720 1725 1730 1735 1740 1745 1750 1755 1760 1765 1770 1775 1780 1785 1790 1795 1800 1805 1810 1815 1820 1825 1830 1835 1840 1845 1850 1855 1860 1865 1870 1875 1880 1885 1890 1895 1900 1905 1910 1915 1920 1925 1930 1935 1940 1945 1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005 2010 2015 2020 2025 2030 2035 2040 2045 2050 2055 2060 2065 2070 2075 2080 2085 2090 2095 2100 2105 2110 2115 2120 2125 2130 2135 2140 2145 2150 2155 2160 2165 2170 2175 2180 2185 2190 2195 2200 2205 2210 2215 2220 2225 2230 2235 2240 2245 2250 2255 2260 2265 2270 2275 2280 2285 2290 2295 2300 2305 2310 2315 2320 2325 2330 2335 2340 2345 2350 2355 2360 2365 2370 2375 2380 2385 2390 2395 2400 2405 2410 2415 2420 2425 2430 2435 2440 2445 2450 2455 2460 2465 2470 2475 2480 2485 2490 2495 2500 2505 2510 2515 2520 2525 2530 2535 2540 2545 2550 2555 2560 2565 2570 2575 2580 2585 2590 2595 2600 2605 2610 2615 2620 2625 2630 2635 2640 2645 2650 2655 2660 2665 2670 2675 2680 2685 2690 2695 2700 2705 2710 2715 2720 2725 2730 2735 2740 2745 2750 2755 2760 2765 2770 2775 2780 2785 2790 2795 2800 2805 2810 2815 2820 2825 2830 2835 2840 2845 2850 2855 2860 2865 2870 2875 2880 2885 2890 2895 2900 2905 2910 2915 2920 2925 2930 2935 2940 2945 2950 2955 2960 2965 2970 2975 2980 2985 2990 2995 3000 3005 3010 3015 3020 3025 3030 3035 3040 3045 3050 3055 3060 3065 3070 3075 3080 3085 3090 3095 3100 3105 3110 3115 3120 3125 3130 3135 3140 3145 3150 3155 3160 3165 3170 3175 3180 3185 3190 3195 3200 3205 3210 3215 3220 3225 3230 3235 3240 3245 3250 3255 3260 3265 3270 3275 3280 3285 3290 3295 3300 3305 3310 3315 3320 3325 3330 3335 3340 3345 3350 3355 3360 3365 3370 3375 3380 3385 3390 3395 3400 3405 3410 3415 3420 3425 3430 3435 3440 3445 3450 3455 3460 3465 3470 3475 3480 3485 3490 3495 3500 3505 3510 3515 3520 3525 3530 3535 3540 3545 3550 3555 3560 3565 3570 3575 3580 3585 3590 3595 3600 3605 3610 3615 3620 3625 3630 3635 3640 3645 3650 3655 3660 3665 3670 3675 3680 3685 3690 3695 3700 3705 3710 3715 3720 3725 3730 3735 3740 3745 3750 3755 3760 3765 3770 3775 3780 3785 3790 3795 3800 3805 3810 3815 3820 3825 3830 3835 3840 3845 3850 3855 3860 3865 3870 3875 3880 3885 3890 3895 3900 3905 3910 3915 3920 3925 3930 3935 3940 3945 3950 3955 3960 3965 3970 3975 3980 3985 3990 3995 4000 4005 4010 4015 4020 4025 4030 4035 4040 4045 4050 4055 4060 4065 4070 4075 4080 4085 4090 4095 4100 4105 4110 4115 4120 4125 4130 4135 4140 4145 4150 4155 4160 4165 4170 4175 4180 4185 4190 4195 4200 4205 4210 4215 4220 4225 4230 4235 4240 4245 4250 4255 4260 4265 4270 4275 4280 4285 4290 4295 4300 4305 4310 4315 4320 4325 4330 4335 4340 4345 4350 4355 4360 4365 4370 4375 4380 4385 4390 4395 4400 4405 4410 4415 4420 4425 4430 4435 4440 4445 4450 4455 4460 4465 4470 4475 4480 4485 4490 4495 4500 4505 4510 4515 4520 4525 4530 4535 4540 4545 4550 4555 4560 4565 4570 4575 4580 4585 4590 4595 4600 4605 4610 4615 4620 4625 4630 4635 4640 4645 4650 4655 4660 4665 4670 4675 4680 4685 4690 4695 4700 4705 4710 4715 4720 4725 4730 4735 4740 4745 4750 4755 4760 4765 4770 4775 4780 4785 4790 4795 4800 4805 4810 4815 4820 4825 4830 4835 4840 4845 4850 4855 4860 4865 4870 4875 4880 4885 4890 4895 4900 4905 4910 4915 4920 4925 4930 4935 4940 4945 4950 4955 4960 4965 4970 4975 4980 4985 4990 4995 5000 5005 5010 5015 5020 5025 5030 5035 5040 5045 5050 5055 5060 5065 5070 5075 5080 5085 5090 5095 5100 5105 5110 5115 5120 5125 5130 5135 5140 5145 5150 5155 5160 5165 5170 5175 5180 5185 5190 5195 5200 5205 5210 5215 5220 5225 5230 5235 5240 5245 5250 5255 5260 5265 5270 5275 5280 5285 5290 5295 5300 5305 5310 5315 5320 5325 5330 5335 5340 5345 5350 5355 5360 5365 5370 5375 5380 5385 5390 5395 5400 5405 5410 5415 5420 5425 5430 5435 5440 5445 5450 5455 5460 5465 5470 5475 5480 5485 5490 5495 5500 5505 5510 5515 5520 5525 5530 5535 5540 5545 5550 5555 5560 5565 5570 5575 5580 5585 5590 5595 5600 5605 5610 5615 5620 5625 5630 5635 5640 5645 5650 5655 5660 5665 5670 5675 5680 5685 5690 5695 5700 5705 5710 5715 5720 5725 5730 5735 5740 5745 5750 5755 5760 5765 5770 5775 5780 5785 5790 5795 5800 5805 5810 5815 5820 5825 5830 5835 5840 5845 5850 5855 5860 5865 5870 5875 5880 5885 5890 5895 5900 5905 5910 5915 5920 5925 5930 5935 5940 5945 5950 5955 5960 5965 5970 5975 5980 5985 5990 5995 6000 6005 6010 6015 6020 6025 6030 6035 6040 6045 6050 6055 6060 6065 6070 6075 6080 6085 6090 6095 6100 6105 6110 6115 6120 6125 6130 6135 6140 6145 6150 6155 6160 6165 6170 6175 6180 6185 6190 6195 6200 6205 6210 6215 6220 6225 6230 6235 6240 6245 6250 6255 6260 6265 6270 6275 6280 6285 6290 6295 6300 6305 6310 6315 6320 6325 6330 6335 6340 6345 6350 6355 6360 6365 6370 6375 6380 6385 6390 6395 6400 6405 6410 6415 6420 6425 6430 6435 6440 6445 6450 6455 6460 6465 6470 6475 6480 6485 6490 6495 6500 6505 6510 6515 6520 6525 6530 6535 6540 6545 6550 6555 6560 6565 6570 6575 6580 6585 6590 6595 6600 6605 6610 6615 6620 6625 6630 6635 6640 6645 6650 6655 6660 6665 6670 6675 6680 6685 6690 6695 6700 6705 6710 6715 6720 6725 6730 6735 6740 6745 6750 6755 6760 6765 6770 6775 6780 6785 6790 6795 6800 6805 6810 6815 6820 6825 6830 6835 6840 6845 6850 6855 6860 6865 6870 6875 6880 6885 6890 6895 6900 6905 6910 6915 6920 6925 6930 6935 6940 6945 6950 6955 6960 6965 6970 6975 6980 6985 6990 6995 7000 7005 7010 7015 7020 7025 7030 7035 7040 7045 7050 7055 7060 7065 7070 7075 7080 7085 7090 7095 7100 7105 7110 7115 7120 7125 7130 7135 7140 7145 7150 7155 7160 7165 7170 7175 7180 7185 7190 7195 7200 7205 7210 7215 7220 7225 7230 7235 7240 7245 7250 7255 7260 7265 7270 7275 7280 7285 7290 7295 7300 7305 7310 7315 7320 7325 7330 7335 7340 7345 7350 7355 7360 7365 7370 7375 7380 7385 7390 7395 7400 7405 7410 7415 7420 7425 7430 7435 7440 7445 7450 7455 7460 7465 7470 7475 7480 7485 7490 7495 7500 7505 7510 7515 7520 7525 7530 7535 7540 7545 7550 7555 7560 7565 7570 7575 7580 7585 7590 7595 7600 7605 7610 7615 7620 7625 7630 7635 7640 7645 7650 7655 7660 7665 7670 7675 7680 7685 7690 7695 7700 7705 7710 7715 7720 7725 7730 7735 7740 7745 7750 7755 7760 7765 7770 7775 7780 7785 7790 7795 7800 7805 7810 7815 7820 7825 7830 7835 7840 7845 7850 7855 7860 7865 7870 7875 7880 7885 7890 7895 7900 7905 7910 7915 7920 7925 7930 7935 7940 7945 7950 7955 7960 7965 7970 7975 7980 7985 7990 7995 8000 8005 8010 8015 8020 8025 8030 8035 8040 8045 8050 8055 8060 8065 8070 8075 8080 8085 8090 8095 8100 8105 8110 8115 8120 8125 8130 8135 8140 8145 8150 8155 8160 8165 8170 8175 8180 8185 8190 8195 8200 8205 8210 8215 8220 8225 8230 8235 8240 8245 8250 8255 8260 8265 8270 8275 8280 8285 8290 8295 8300 8305 8310 8315 8320 8325 8330 8335 8340 8345 8350 8355 8360 8365 8370 8375 8380 8385 8390 8395 8400 8405 8410 8415 8420 8425 8430 8435 8440 8445 8450 8455 8460 8465 8470 8475 8480 8485 8490 8495 8500 8505 8510 8515 8520 8525 8530 8535 8540 8545 8550 8555 8560 8565 8570 8575 8580 8585 8590 8595 8600 8605 8610 8615 8620 8625 8630 8635 8640 8645 8650 8655 8660 8665 8670 8675 8680 8685 8690 8695 8700 8705 8710 8715 8720 8725 8730 8735 8740 8745 8750 8755 8760 8765 8770 8775 8780 8785 8790 8795 8800 8805 8810 8815 8820 8825 8830 8835 8840 8845 8850 8855 8860 8865 8870 8875 8880 8885 8890 8895 8900 8905 8910 8915 8920 8925 8930 8935 8940 8945 8950 8955 8960 8965 8970 8975 8980 8985 8990 8995 9000 9005 9010 9015 9020 9025 9030 9035 9040 9045 9050 9055 9060 9065 9070 9075 9080 9085 9090 9095 9100 9105 9110 9115 9120 9125 9130 9135 9140 9145 9150 9155 9160 9165 9170 9175 9180 9185 9190 9195 9200 9205 9210 9215 9220 9225 9230 9235 9240 9245 9250 9255 9260 9265 9270 9275 9280 9285 9290 9295 9300 9305 9310 9315 9320 9325 9330 9335 9340 9345 9350 9355 9360 9365 9370 9375 9380 9385 9390 9395 9400 9405 9410 9415 9420 9425 9430 9435 9440 9445 9450 9455 9460 9465 9470 9475 9480 9485 9490 9495 9500 9505 9510 9515 9520 9525 9530 9535 9540 9545 9550 9555 9560 9565 9570 9575 9580 9585 9590 9595 9600 9605 9610 9615 9620 9625 9630 9635 9640 9645 9650 9655 9660 9665 9670 9675 9680 9685 9690 9695 9700 9705 9710 9715 9720 9725 9730 9735 9740 9745 9750 9755 9760 9765 9770 9775 9780 9785 9790 9795 9800 9805 9810 9815 9820 9825 9830 9835 9840 9845 9850 9855 9860 9865 9870 9875 9880 9885 9890 9895 9900 9905 9910 9915 9920 9925 9930 9935 9940 9945 9950 9955 9960 9965 9970 9975 9980 9985 9990 9995 10000 10005 10010 10015 10020 10025 10030 10035 10040 10045 10050 10055 10060 10065 10070 10075 10080 10085 10090 10095 10100 10105 10110 10115 10120 10125 10130 10135 10140 10145 10150 10155 10160 10165 10170 10175 10180 10185 10190 10195 10200 10205 10210 10215 10220 10225 10230 10235 10240 10245 10250 10255 10260 10265 10270 10275 10280 10285 10290 10295 10300 10305 10310 10315 10320 10325 10330 10335 10340 10345 10350 10355 10360 10365 10370 10375 10380 10385 10390 10395 10400 10405 10410 10415 10420 10425 10430 10435 10440 10445 10450 10455 10460 10465 10470 10475 10480 10485 10490 10495 10500 10505 10510 10515 10520 10525 10530 10535 10540 10545 10550 10555 10560 10565 10570 10575 10580 10585 10590 10595 10600 10605 10610 10615 10620 10625 10630 10635 10640 10645 10650 10655 10660 10665 10670 10675 10680 10685 10690 10695 10700 10705 10710 10715 10720 10725 10730 10735 10740 10745 10750 10755 10760 10765 10770 10775 10780 10785 10790 10795 10800 10805 10810 10815 10820 10825 10830 10835 10840 10845 10850 10855 10860 10865 10870 10875 10880 10885 10890 10895 10900 10905 10910 10915 10920 10925 10930 10935 10940 10945 10950 10955 10960 10965 10970 10975 10980 10985 10990 10995 11000 11005 11010 11015 11020 11025 11030 11035 11040 11045 11050 11055 11060 11065 11070 11075 11080 11085 11090 11095 11100 11105 11110

characterised in that the radio frequency shield comprises: a dielectric layer having first and second faces and extending circumferentially around the examination region; a plurality of first metal strips disposed on the first face of the dielectric layer extending parallel to a longitudinal axis of the bore; a plurality of second metal strips disposed on the second face of the dielectric layer extending parallel to the longitudinal axis, the second metal strips being offset circumferentially relative to the first metal strips such that each of the first metal strips is capacitively coupled to two of the second metal strips and each of the second metal strips is capacitively coupled to two of the first metal strips; and low impedance interconnections interconnecting each of the metal strips with adjacent metal strips, the low impedance interconnections being longitudinally offset to prevent low frequency and direct currents from flowing in a loop circumferentially around the radio frequency shield.

Preferably the apparatus further includes a plurality of low impedance connections connect the plurality of first metal strips with the plurality of second metal strips.

In an apparatus according to the invention the low impedance interconnections are suitably disposed alternately adjacent opposite ends of the strips such that low frequency and direct currents are constrained to flow in a zig-zag path.

The radio frequency coil is suitably a birdcage style coil having a pair of end rings extending circumferentially around the bore adjacent the radio frequency shield, the low impedance interconnections being disposed generally in alignment with the birdcage style radio frequency coil end rings.

According to a second aspect of the invention there is provided a magnetic resonance method for use with a magnetic resonance apparatus that includes a primary magnet assembly for generating a temporally constant magnetic field through an examination region in a bore thereof, a gradient coil assembly mounted in the bore for causing magnetic field gradients within the examination region, a radio frequency coil assembly disposed within the gradient coil assembly for transmitting radio frequency pulses into the examination region, and a radio frequency shield disposed between the gradient coil assembly and the radio frequency coil assembly; the method including generating the temporally constant magnetic field longitudinally through the examination region; inducing magnetic field gradient pulses across the examination region with the gradient coil assembly; and applying radio frequency pulses to the examination region with the radio frequency coil assembly; and being characterized by: passing radio frequency eddy currents induced in the radio frequency shield by the radio frequency coil assembly circumferentially around the shield while blocking gradient coil frequency eddy currents induced by the gradient coil assembly from passing circumferentially around the radio frequency shield; and permitting the gradient coil frequency eddy currents induced in the radio frequency shield to travel along meandering paths having primarily

longitudinal components with minimal circumferential components.

One advantage of the present invention is that it reduces radio frequency shielding.

Another advantage of the present invention is that it reduces electrical arcing and the associated noise.

Another advantage of the present invention is that it minimizes gradient and kilohertz range eddy currents.

One magnetic resonance apparatus in accordance with the invention and its method of operation in accordance with the invention will now be described, by way of example, with reference to the accompanying drawings in which:-

FIGURE 1 is a diagrammatic illustration of the apparatus;

FIGURE 2 is an enlarged cross-sectional view of gradient and radio frequency coil assemblies of the apparatus.

FIGURE 3 is a diagrammatic illustration depicting an RF shield of the apparatus in conjunction with a dielectric cylindrical former;

FIGURE 4 is a cross-sectional view of the RF shield of FIGURE 3 through section 4-4; and,

FIGURE 5 illustrates an alternate embodiment of the RF shield in which a meandering low impedance connection path is generally aligned with the end rings of a birdcage RF coil.

With reference to FIGURE 1, the apparatus includes a plurality of superconducting primary magnetic field coils 10 which along with shield coils 12 generate a primary magnetic field extending along a longitudinal or z-axis of a central bore 14. The primary magnetic field is temporally constant and substantially uniform through an imaging region at the geometric center of the bore 14. The superconducting coils 10, 12 are held in a helium can 16 which chills the coils to their superconducting temperature. To reduce helium boil-off,

the superconducting magnetic field coils and the helium can are surrounded by cold shields 18 and a vacuum dewar 20. The dewar 20 is a toroidal vacuum vessel which extends around the central bore 14. The vacuum vessel includes an inner cylindrical wall 22.

With continuing reference to FIGURE 1 and further reference to FIGURE 2, a primary gradient coil assembly 30 is mounted inside the inner wall 22 of the toroidal vacuum vessel. The gradient coil assembly includes a cylindrical former 32 of a dielectric material such as glass-reinforced epoxy. The z-gradient coils 34 are wrapped around the dielectric former 32. y-gradient coils 36 are wrapped around the z-gradient coils and x-gradient coils 38 are wrapped around the y-gradient coils. In the preferred embodiment, the x and y-gradient coils are thumbprint or distributed gradient coils, although bunched gradient coils can also be used. Preferably, the gradient coil assembly is a self-shielded gradient coil assembly. To this end, x, y, and z-gradient shield coils 40 surround the primary gradient coil

50

55

60

65

70

75

80

85

90

95

100

105

110

115

120

125

130

135

140

145

150

155

160

165

170

175

180

185

190

195

200

205

210

215

220

225

230

235

240

245

250

255

260

265

270

275

280

285

290

295

300

305

310

315

320

325

330

335

340

345

350

355

360

365

370

375

380

385

390

395

400

405

410

415

420

425

430

435

440

445

450

455

460

465

470

475

480

485

490

495

500

505

510

515

520

525

530

535

540

545

550

555

560

565

570

575

580

585

590

595

600

605

610

615

620

625

630

635

640

645

650

655

660

665

670

675

680

685

690

695

700

705

710

715

720

725

730

735

740

745

750

755

760

765

770

775

780

785

790

795

800

805

810

815

820

825

830

835

840

845

850

855

860

865

870

875

880

885

890

895

900

905

910

915

920

925

930

935

940

945

950

955

960

965

970

975

980

985

990

995

1000

1005

1010

1015

1020

1025

1030

1035

1040

1045

1050

1055

1060

1065

1070

1075

1080

1085

1090

1095

1100

1105

1110

1115

1120

1125

1130

1135

1140

1145

1150

1155

1160

1165

1170

1175

1180

1185

1190

1195

1200

1205

1210

1215

1220

1225

1230

1235

1250

1260

1270

1280

1290

1300

1310

1320

1330

1340

1350

1360

1370

1380

1390

1400

1410

1420

1430

1440

1450

1460

1470

1480

1490

1500

1510

1520

1530

1540

1550

1560

1570

1580

1590

1600

1610

1620

1630

assembly 30. The primary and shield gradient coils 30, 40 generate gradient magnetic fields such that the gradient fields of the two coils combine within the examination region to produce a linear gradient and cancel outside the central bore 14. In the preferred embodiment, the shield gradient coils are mounted on a surface of the toroidal vacuum vessel cylinder 22. Magnetic field shims, not shown, are inserted in the annular gap between the primary and shield gradient coils 30, 40.

A radio frequency coil assembly 50 is mounted within the primary gradient coil assembly 30. More specifically to the preferred embodiment, the radio frequency coil assembly includes a dielectric former 52 on which a birdcage style coil 54 is mounted. A bore liner 56 is disposed inside the birdcage coil assembly and extends the length of the central bore to provide a cosmetic covering for the radio frequency and gradient coil assemblies.

With continuing reference to FIGURES 1 and 2, and particular reference to FIGURE 3, a radio frequency or RF coil shield 60 is disposed between the radio frequency coil assembly 50 and the primary gradient coils 34, 36, and 38. In the preferred embodiment, the radio frequency shield 60 is applied to an external surface of the cylindrical dielectric former 32 before the primary x, y, and z-gradient coils are applied. Alternately, the radio frequency shield 60 is mounted to an inner surface of the dielectric former 32.

The radio frequency shield 60 in the preferred embodiment, is a double-sided circuit board which includes a central dielectric layer 62 which has layers of metal, preferably copper, foil 64, 66 adhered to opposite sides. The dielectric material is thin and flexible such that it can be wrapped easily around the dielectric cylinder. Teflon, fiber-reinforced epoxy, or the like, are suitable dielectric layers. The copper layers 64, 66 are etched or cut, in the preferred embodiment, to define a series of gaps 70 extending in a direction parallel to the longitudinal axis, leaving metal or copper strips 72 therebetween. Thin bridges 74 interconnect adjacent metal strips 72 at adjacent opposite ends thereof. In this manner, a meandering, generally S-shaped low impedance path is defined by adjacent strips 72. In the preferred embodiment, the copper layers are half ounce copper, the longitudinal strips are about 35 mm wide and are separated by gaps of about 0.175 mm. Three low impedance bridges, each about 1 cm wide, connect the strips at alternating ends. The bridges may be etched to a reduced height.

With continuing reference to FIGURE 3 and further reference to FIGURE 4, analogous metallic strips 72 with interconnecting low impedance bridges are provided on both surfaces of the dielectric layer 62. However, the strips are offset such that each strip 72 on one side of the dielectric layer overlaps a pair of adjoining strips 72 on the opposite side of the dielectric layer. In the illustrated embodiment, the overlap is about 17.5 mm. Four tabs 76 provide low impedance paths between the electrical conductors on opposite sides of

the dielectric layer. The tabs are arranged with quadrature symmetry, i.e., if such tabs are introduced at each end and at equidistant points around the circumference. The tabs 76 also make convenient attachment points for ground connections. The length of the dielectric sheet is selected such that it extends circumferentially around the dielectric former 32 with the end metallic strips lapping analogous to the previously described metallic strips. Preferably at least 32 strips are provided on each surface circumferentially around the dielectric cylinder 32, the preferred embodiment having about 64 strips. The low impedance path between the conductive strips on opposite sides prevents arcing across the dielectric sheet 62. This is particularly important due to the short path length at the edges of the sheets.

The lapped metallic strips on opposite faces and the dielectric sheet itself provide capacitive interconnections between the two sides of the shield. Radio frequency currents induced in the shield flow in an azimuthal or circumferential direction around the shield through the capacitors formed by the overlapping strips and the dielectric layer in between. Capacitance, neglecting fringing effects, is defined by:

$$C = \epsilon \frac{A}{d} \quad (1).$$

where  $\epsilon$  is the permittivity of the dielectric,  $A$  is the area of the dielectric between the lapped strips, and  $d$  is the dielectric thickness. Thus, to maximize current flow within the shield, the capacitance is maximized by using a dielectric which is very thin and has a high permittivity relative to the permittivity of air. The narrow gap between two adjacent strips also provides some capacitive coupling, with  $c$  being the permittivity of air or epoxy potting medium when integrated with the gradient coil assembly.  $A$  being the area of the etched side of each strip, and  $d$  being the width of the spacing between strips. In this manner, limited high frequency current flow is provided from strip to strip in the azimuthal direction on each side independently of the others.

Audio frequency, particularly gradient, eddy currents are prevented from flowing in the azimuthal direction by this capacitance. The impedance presented by these capacitive couplings is inversely proportional to frequency. Thus, audio or kilohertz frequency gradient eddy currents are blocked while radio, particularly megahertz frequency eddy currents are not. The bridges connecting the longitudinal strips are disposed adjacent opposite ends only so that complete rings are not formed. Hence, the bridges do not contribute to eddy currents by providing direct circumferential low frequency flow paths. At each end, only every second pair of strips is shorted. Only minimal low frequency eddy currents are generated in the longitudinal direction and any that do flow would tend to create predominantly a  $B_x$  or  $B_y$  field (hence, the RF shielding effect). Accordingly, the continuous longitudinal path is not of particular concern for gradient pulsing but provides good RF screening.

Arcing between individual strips on each side of the shield is eliminated by the presence of the bridges. The bridges prevent high voltage levels from building up between adjacent copper strips. Arcing between the two sides of the shield through or around the dielectric layer is prevented by shorting the two sides of the shield together at the four symmetric points 76. The four points 76 are chosen to maintain quadrature symmetry.

With reference to FIGURE 5, various alternate etching paths may be provided and various other dielectric materials may be used. Although the fiber reinforced epoxy is used in the preferred embodiment, Teflon, a more expensive material, has a lower permittivity and has a low dielectric loss tangent. Accordingly, the Q-factor of the RF coil that is placed within the shield is not damped as much with Teflon as with the fiber-reinforced epoxy shield. Those skilled in the art will appreciate that there are a plethora of other dielectrics which may be used in the construction of the shield.

In the embodiment of FIGURE 5, the bridges 74 are positioned a short distance from each end of the cylinder. The bridges are substantially in longitudinal alignment with end rings 78 of the birdcage coil 54. In yet another variation, different numbers of bridges may be provided such as 1, 2, 4, or the like between longitudinal strips.

With reference again to FIGURE 1, a sequence control processor 80 accesses a memory to load one of a plurality of predefined magnetic resonance imaging sequences. The sequence control processor 80 controls a gradient current control 82 and a transmitter 84 to cause the formation of radio frequency and gradient pulses in accordance with the loaded magnetic resonance sequence. The gradient coil controller 82 is connected with a series of current pulse amplifiers 86 which, in turn, supply current pulses to the appropriate primary gradient coils 34, 36, and 38 and shield gradient coils. The transmitter 84, preferably a digital transmitter, is connected with the radio frequency coil 54 for generating radio frequency pulses for exciting and manipulating magnetic resonance in selected dipoles of a portion of a subject within the examination region. A radio frequency receiver 88, preferably a digital receiver, is connected with the radio frequency coil or surface coils (not shown) for demodulating magnetic resonance signals emanating from the examined portion of the subject. An image reconstruction processor 90 reconstructs the received resonance signals into an electronic image representation using conventional reconstruction algorithms such as an inverse two-dimensional Fourier transform reconstruction. The image representations are stored in an image memory 92. A video processor 94 converts selected portions of the electronic images stored in the image memory 92 into appropriate format for display on a video, LCD, active matrix, or other monitor 96.

## Claims

1. A magnetic resonance apparatus including a magnet assembly (10) for generating a temporally constant magnetic field longitudinally through an examination region disposed in a central longitudinal bore (14) thereof, a gradient coil assembly (30) including gradient coils (34, 36, 38) for generating magnetic field gradients along three mutually orthogonal axes within the examination region, the gradient coil assembly (30) being disposed around the examination region, a radio frequency coil assembly (50) including a radio frequency coil (54) disposed around the examination region and adjacent the gradient coil assembly (30), and a radio frequency shield (60) disposed between the gradient coils (34, 36, 38) and the radio frequency coil (54), characterised in that the radio frequency shield (60) comprises: a dielectric layer (62) having first and second faces, and extending circumferentially around the examination region; a plurality of first metal strips (72) disposed on the first face of the dielectric layer (62) extending parallel to a longitudinal axis of the bore (14); a plurality of second metal strips (72) disposed on the second face of the dielectric layer (62) extending parallel to the longitudinal axis, the second metal strips (72) being offset circumferentially relative to the first metal strips (72) such that each of the first metal strips (72) is capacitively coupled to two of the second metal strips (72) and each of the second metal strips (72) is capacitively coupled to two of the first metal strips (72); and low impedance interconnections (74) interconnecting each of the metal strips (72) with adjacent metal strips (72) the low impedance interconnections (74) being longitudinally offset to prevent low frequency and direct currents from flowing in a loop circumferentially around the radio frequency shield (60).
2. An apparatus as set forth in claim 1: wherein a plurality of low impedance connections (76) connect the plurality of first metal strips (72) with the plurality of second metal strips (72).
3. An apparatus as set forth in claim 2 wherein by the low impedance connections (76) between the first and second metal strips (72) are arranged with quadrature symmetry.
4. An apparatus as set forth in any preceding claim wherein the low impedance interconnections (74) are disposed alternately adjacent opposite ends of the strips (72) such that low frequency and direct currents are constrained to flow in a zig-zag path.
5. An apparatus as set forth in any preceding claim wherein the radio frequency coil (54) is a birdcage style coil having a pair of end rings (78) extending

- circumferentially around the bore (14) adjacent to the radio frequency shield (60), the low impedance interconnections (74) being disposed generally in alignment with the birdcage style radio frequency coil end rings (78). 5
6. An apparatus as set forth in any preceding claim wherein the gaps (70) between the first and second metal strips (72) are defined by removing metal foil from first and second continuous foil sheets (64, 66) and the low impedance interconnections are defined by interrupting the metal foil removal. 10
7. An apparatus as set forth in any preceding claim wherein the low impedance interconnections include capacitive elements. 15
8. An apparatus as set forth in any preceding claim wherein the gradient coil assembly (30) includes a dielectric former (32) and the radio frequency shield (60) is mounted around an exterior surface of the dielectric former (32) and the gradient coils (34, 36, 38) are mounted around the radio frequency shield (60). 20
9. A magnetic resonance method for use with a magnetic resonance apparatus that includes a primary magnet assembly (10) for generating a temporally constant magnetic field through an examination region in a bore (14) thereof, a gradient coil assembly (30) mounted in the bore (14) for causing magnetic field gradients within the examination region, a radio frequency coil assembly (50) disposed within the gradient coil assembly (30) for transmitting radio frequency pulses into the examination region, and a radio frequency shield (60) disposed between the gradient coil assembly (30) and the radio frequency coil assembly (50); the method including: generating the temporally constant magnetic field longitudinally through the examination region; inducing magnetic field gradient pulses across the examination region with the gradient coil assembly (30); and applying radio frequency pulses to the examination region with the radio frequency coil assembly (50); and being characterized by: 25 passing radio frequency eddy currents induced in the radio frequency shield (60) by the radio frequency coil assembly (50) circumferentially around the shield (60) while blocking gradient coil frequency eddy currents induced by the gradient coil assembly (30) from passing circumferentially around the radio frequency shield (60); and permitting the gradient coil frequency eddy currents induced in the radio frequency shield (60) to travel along meandering paths having primarily longitudinal components with minimal circumferential components. 30
10. A method as set forth in claim 9 wherein the radio frequency shield (60) includes a plurality of longitudinally extending strips (72) having low impedance bridges (74) interconnecting adjacent strips (72) near opposite ends thereof, the induced gradient frequency eddy currents flowing longitudinally along one strip (72), crossing a bridge (74) to an adjacent strip (74), flowing longitudinally along the adjacent strip (72), crossing a low impedance bridge (74) to a next adjacent strip, flowing longitudinally across the next adjacent strip (72), and so on until the gradient frequency eddy currents die out. 35

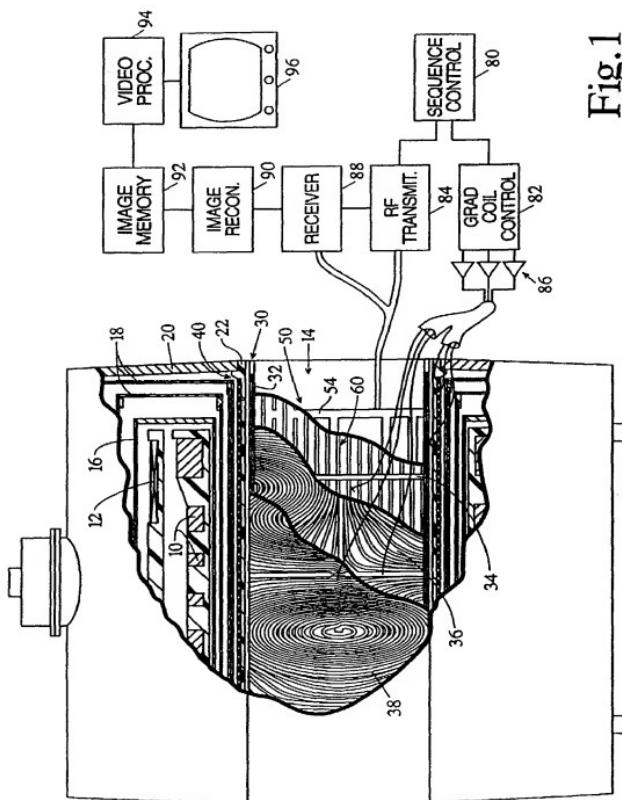
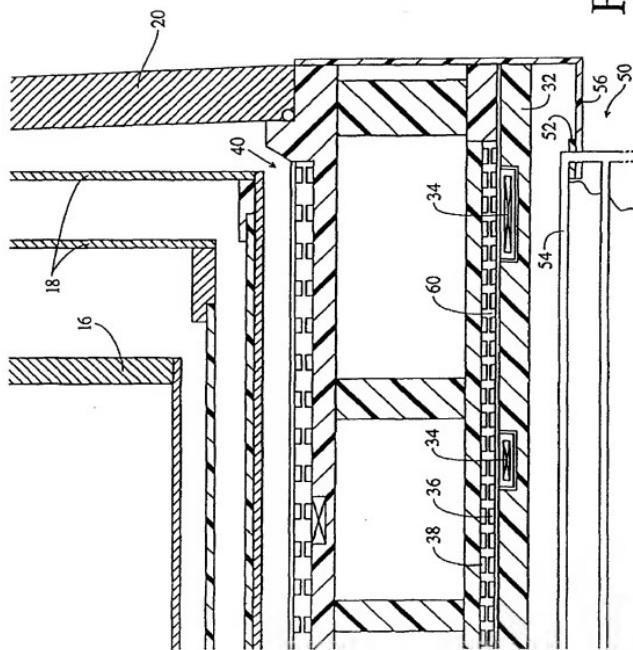
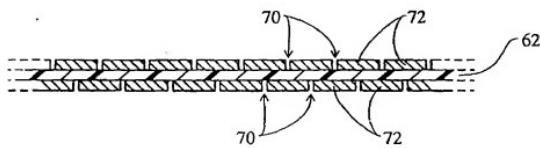
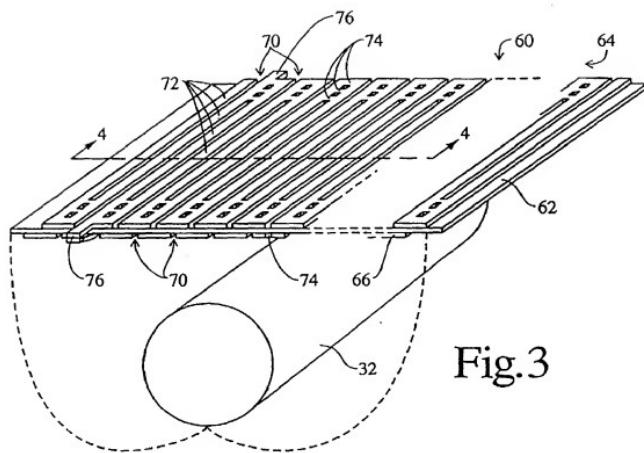


Fig. 1

Fig.2





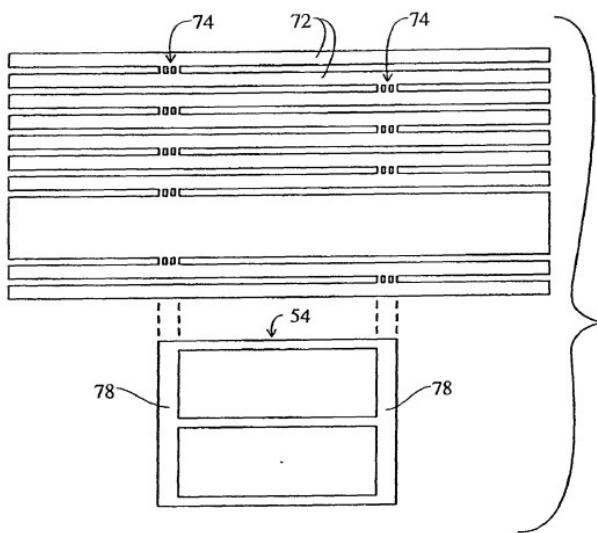


Fig.5



European Patent  
Office

## EUROPEAN SEARCH REPORT

Application Number  
EP 95 30 9282

DOCUMENTS CONSIDERED TO BE RELEVANT		
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim
X	US-A-5 372 137 (E.C. WONG, J.S. HYDE)	1-3,5, 7-10 4,6
A	* column 2, line 49 - column 3, line 38 * * column 5, line 41 - column 6, line 9 * * column 7, line 15 - line 48 * * figures 3-6 *	
X	EP-A-0 151 726 (GENERAL ELECTRIC COMPANY)	1-3,5, 7-10 4,6
A	* page 3, line 10 - line 22 * * page 4, line 29 - page 6, line 16 * * page 8, line 14 - page 9, line 34 * * figures 2-4,6,7 *	
D	& US-A-4 642 569	
X	EP-A-0 288 579 (THOMSON-CGR) * column 3, line 41 - column 6, line 26 * * figures 1,2 *	1-3,6-8
A	US-A-5 367 261 (P.S. FREDERICK) * column 2, line 44 - line 66 * * column 6, line 45 - column 7, line 43 * * figures 2,4 *	1-3,5-10
The present search report has been drawn up for all claims		
Place of search		Date of completion of the search
THE HAGUE		14 May 1996
Examiner		
Volmer, W		
CATEGORY OF CITED DOCUMENTS		
X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technical background O : non-written disclosure P : intermediate document		
T : theory or principle underlying the invention E : earlier patent document, not published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document		